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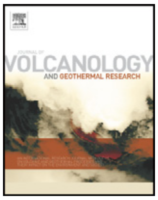

Experimental birth of a maar–diatreme volcano

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ABSTRACT

Maar–diatreme eruptions are hazardous to people and infrastructure, and are also linked to the formation of the kimberlitic variety of diatremes, which is important economically. Processes occurring in the subsurface diatreme and their relation to surface eruptions are not yet well understood. We conducted field-scale experiments using analog materials to shed more light on these processes, especially the formation of the proto-diatreme during the first explosions of a maar eruption. Specifically, a series of buried explosions in a prepared, layered substrate (pad) produced craters, extra-crater deposits and sub-crater deposits analogous to volcanic maar craters, tephra rings and incipient diatremes. Post-explosion substrate excavation revealed that single large explosions produce sub-crater deposits extending nearly to the crater-rim crest. The same energy divided into three blasts, either co-located or at different depths with the same epicenter, produced narrower and sometimes deeper sub-crater deposits even though the final sizes of the craters were similar to that produced by the single large blast. The sub-crater deposits have an upper zone with domains from different substrate depths, and an underlying zone distinguished primarily by being more loosely packed than the original substrate. Videos show surface motion extending beyond the post-shot crater rim, and largely vertical ejection and fallback of material into the footprint of these deposits, especially for the explosions that occurred below optimal depth of burial. We infer that much of the loosely packed material was disassembled, vertically transported to different heights during the explosions, then fell back without significant *relative lateral* movement of grains. However, subvertical fallback did produce apparent cross-cutting structures in shallow sub-crater deposits. One explosion ejected material from the deepest substrate horizon, but it was redeposited only within the crater and is unrepresented in the ejecta rim. Implications of the experiments for maar–diatreme volcanoes, including some kimberlite pipes, are as follows: (1) vertical focusing of deep explosions in the diatreme explains the deficit of deep wallrock lithics observed at maar volcanoes; (2) direct vertical fallback is possibly an important process forming diatreme deposits, especially during the earliest stages; and (3) even in our limited simulation the number and scaled depth of explosions clearly affect proto-diatreme size and structure.

1. Introduction

Maars are the second-most common type of volcanic landform on continents and islands, after scoria cones (e.g., Wood, 1980; Cas and Wright, 1987; Wohletz and Heiken, 1992). Their eruptions, which are strongly affected by explosive interaction of rising magma and groundwater, are hazardous to people and property (e.g., Lorenz, 2007; Sottili et al., 2009; Taddeucci et al., 2010). Underneath the maar crater sits a diatreme, a subterranean structure cut into the country rock (or soft deposits) and filled by pyroclastic debris and broken-up country rock (e.g., Cloos, 1941; Lorenz, 1986; Lorenz and Kurszlaukis, 2007; Valentine et al., 2011; White and Ross, 2011). Kimberlitic diatremes can contain diamonds (e.g., Kjarsgaard, 2007 and references therein), so diatremes are important both from volcanic hazards and economic perspectives. The processes that form diatremes and occur inside them are not yet agreed upon, and the locations of explosion sites in the diatreme and relationship between diatreme and tephra ring evolution remain uncertain (Lorenz and Kurszlaukis, 2007; Valentine and White, 2012). Diatreme processes can be partly deciphered from studying diatreme and maar deposits (e.g., White, 1991; Ross and White, 2006; Valentine, 2012), and insights can be obtained from observations of historical maar eruptions (as reviewed by Kienle et al., 1980; Lorenz, 1986; and White and Ross, 2011). The latter shows that maars and their tephra rings, and by implication diatremes, are formed by many discrete phreatomagmatic eruptive pulses (reflecting individual explosions), which sometimes combine into more sustained eruptive phases (e.g., Moore et al., 1966).

Analog laboratory experiments have also been attempted to model diatreme or kimberlite emplacement processes. Workers such as McCallum et al. (1975), Woolsey et al. (1975), Walters et al. (2006) and Gernon et al. (2009) have focused on gas fluidization. In their experiments, gas was injected below a bed of granular material,

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typically over several minutes, and structures similar in appearance to diatremes were formed due to the passage of the gas. Their inference is that natural full-scale diatremes also result from, or at least are strongly influenced by, gas fluidization in a granular medium. However this does not match the discrete eruptive pulses observed in maar–diatreme volcanoes.

Different bench-scale analog experiments were conducted by Ross et al. (2008a,b) to model a specific diatreme process: debris jets. These hypothetical upward moving flows propagate inside diatremes from explosion sites and contain gas, lithics, juvenile particles, and perhaps liquid water. The Ross et al. (2008a,b) experiments injected, as discrete pulses (mimicking individual magma–water explosions), mixtures of colored glass beads and compressed air into other non-fluidized glass beads. One interesting result was that an "eruption" (ejection of particles in the air) was not necessary to produce the cross-cutting bodies of volcaniclastic material often observed in diatremes, including kimberlitic examples: debris jetting can be fully subterranean processes. The features produced by the experiments have some similarities to features produced by fluidization (preceding paragraph), showing that sustained gas flux is not a necessary condition. These experiments, however, did not attempt to fully model the creation and evolution of diatremes.

To get closer to the natural scale of a maar–diatreme volcano, medium- to large-scale experiments can be conducted in the field. Diatreme formation and maar crater formation are directly linked, and result from explosive processes, so an interesting approach is to use chemical explosives to produce craters and sub-crater deposits. High explosives produce discrete, high-energy events as would occur during formation of a natural maar–diatreme. Previous field-scale experimental studies of volcanic cratering have linked aspects of particle ejection and crater formation to depth and energy of individual explosions (e.g., Goto et al., 2001; Ohba et al., 2002), but to our knowledge, none have focused on sub-crater deposits and structures. Also, previous experiments used only single charges. Here we report field-scale experimental results from single and multiple buried explosions that cratered the ground, expelling material then deposited both as extra-crater ejecta and sub-crater deposits (fallback) that represent incipient diatremes. Our results have important implications for the understanding of maar–diatreme volcanoes and some kimberlite pipes.

2. General cratering phenomena and definitions

2.1. Explosive cratering

Before discussing our experiments we summarize some of what is known about explosive cratering in the literature to provide context. The following account is based mostly on information reported in Nordyke (1961), Bening and Kurtz (1967), and Schoutens (1979) for chemical and nuclear explosives.

The depth at which a buried explosive charge produces the largest possible crater is called "optimum depth of burial" and is proportional to the cube root of explosion energy, $E^{1/3}$ (Goto et al., 2001). Buried explosions have been studied extensively. Chemical explosions at optimum depth of burial create highly compressed gases that expand outward from the charge location, initially in a sphere (Fig. 1A). A compression wave propagates radially outward. As it hits the free surface it reflects back as a rarefaction wave. This makes particles near the free surface accelerate upwards ("spall"; Fig. 1B). Spalling is a minor process for explosions at optimum depth, relative to explosions at lesser depths. The rarefaction wave contributes to damaging of material that will not be expelled by the blast. When the rarefaction reaches it, the cavity begins to expand rapidly upward and it lifts its roof in a dome shape (Fig. 1C–D). The dome eventually disintegrates, a process also known as "gas venting", which sends individual particles along ballistic trajectories (Fig. 1E). Some slumping of the walls of the transient crater may occur during gas venting. Eventually all particles fall back down (Fig. 1F) and a post-shot crater is left (Fig. 1G).

2.2. Definitions of terms related to experimental cratering

Scaled depth is the physical depth of an explosion divided by $E^{1/3}$. *Ejecta* is the material permanently ejected by the explosion, landing on or beyond the rim of the post-shot crater. *Fallback* is the material, dissociated and lifted by the explosion, which has fallen back within the transient crater. Fallback can also be described as "sub-crater deposits" because the deposits occur under the floor of the post-shot crater. The *transient crater* is "the boundary of the crater representing the limit of dissociation of the medium by the explosion" (Rooke et al., 1974). It exists only during the explosion, and is also known as the "true crater" (not used here) in the cratering literature. The *post-shot crater* is the crater left at the end of the explosion, also known as the "apparent crater" (not used here) in the literature. Finally, the *damage zone* comprises the material below and beyond the transient crater that has been disturbed (irreversibly modified) by the explosion but not substantially moved.[1]

2.3. Definitions of terms related to maar–diatreme volcanoes

A review by White and Ross (2011) of maar–diatreme volcanoes contains definitions of terms such as "syn-eruptive crater" or "diatreme deposits" that will be useful to quote and discuss here to facilitate comparison between our experiments and nature. A *maar* is "a volcano characterized by a central crater cut into the pre-eruptive ground, surrounded by an ejecta ring, and underlain by a diatreme". A maar *ejecta ring* consists of "ejecta deposited on the pre-eruptive ground around the maar crater". Typically these numerous and thin ejecta layers are deposited by dilute pyroclastic density currents, a.k.a. "base surges", and subordinate fallout and ballistics from an eruption plume (e.g., Moore et al., 1966; Kienle et al., 1980; Self et al., 1980). In contrast, in the current experiments, much of the ejecta that landed beyond the crater was not transported by pyroclastic density currents.

A *crater* is a "pit open to the sky". One can distinguish between the *syn-eruptive crater*, which exists during the eruption and the *post-eruptive crater*, which is the crater left at the end of the eruption. *Crater-fill deposits* are "deposits of any type and origin filling the post-eruptive crater". *Diatreme deposits* are the "primary volcaniclastic infill of the diatreme structure"; they include pyroclastic deposits formed during the eruption and deposited on the floor of the syn-eruptive crater. These can include both pyroclastic density current deposits and fallout from an eruption column. An *intra-diatreme fragmentation zone* is a "chaotic zone of irregular form and including coherent and clastic rock, but not in contact with country rock". Such zones should be surrounded by normal diatreme material and are inferred to represent sites of phreatomagmatic explosions within the diatreme, but at levels higher than the root zone (White and Ross, 2011).

The terms "syn-eruptive crater" and "transient crater" are not synonymous. The first term refers to the crater existing during the maar–diatreme eruption, in general: this crater can exist for days or weeks. In contrast, a transient crater only exists during a specific explosion, and fallback material partly fills it within a short timeframe. In large maars with multiple explosions occurring over time, transient craters from small individual explosions are probably smaller than the overall syn-eruptive crater, in the same way that a "vent" can be smaller than the syn-eruptive crater.

A final clarification relates to the words "eruption" and "explosion": a volcanic eruption is a phenomenon observed at the surface, typically called explosive if it vigorously delivers particles to the atmosphere, whereas an explosion is a violent expansion. In our system chemical

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[1] In a hard-rock environment, the damage zone around diatremes and root zones is manifested by "contact breccias" or "explosion breccias" (e.g., Clement, 1982; Clement and Reid, 1989; Lorenz and Kurszlaukis, 2007).